ASD TR-7-888 (I)

ASD INTERIM REPORT 7-888 (I)
September 1961

DEVELOPMENT OF ULTRASONIC WELDING EQUIPMENT FOR REFRACTORY METALS

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AEROPROJECTS INCORPORATED
West Chester, Pennsylvania

Contract: AF33(600)-43026
ASD Project No. 7-888

Interim Technical Engineering Report
1 June 1961 to 31 August 1961

Joining refractory and superalloy metals in thicknesses up to 0.10 inch by ultrasonic welding is feasible. A first approximation of the acoustical energy required indicates that the requisite equipment is also feasible. This report is a compilation and discussion of information pertinent to the development of ultrasonic welding equipment for joining AM-355 steel, Inconel X, Rene 41, tungsten, molybdenum-0.5% titanium, and columbium alloy (duPont D-31).

FABRICATION BRANCH
MANUFACTURING TECHNOLOGY LABORATORY

AFSC Aeronautical Systems Division
United States Air Force
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ABSTRACT-SUMMARY
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DEVELOPMENT OF ULTRASONIC WELDING EQUIPMENT
FOR REFRACTORY METALS

J. Byron Jones
et al
Aeroprojects Incorporated

Joining refractory and superalloy metals in thicknesses up to 0.10 inch by ultrasonic welding is feasible. A first approximation of the acoustical energy required indicates that the requisite welding equipment is also feasible. This report is a compilation and discussion of information pertinent to the development of ultrasonic welding equipment for joining AM-355 steel, Inconel X, René 41, tungsten, molybdenum-0.5% titanium, and columbium alloy (duPont D-31).

The feasibility of welding the materials and gages of interest is supported by data, appropriately referenced, from previous work with thinner material. Information on transducer, coupler, and tip materials is presented with information on evaluating efficiency and practicability. Design information on spot-type and roller-seam welding machine tips is presented. Data on various properties of the weldment materials are tabulated.

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FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF33(600-43026 from 1 June 1961 to 31 August 1961. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Aeroprojects Incorporated of West Chester, Pennsylvania, was initiated under ASD Manufacturing Technology Project 7-888, "Development of Ultrasonic Welding Equipment for Refractory Metals". It was administered under the direction of Fred Miller (ASRCTF) of the Fabrication Branch, Manufacturing Technology Laboratory, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

The project is being conducted under J. Byron Jones, Aeroprojects Director of Research; with Nicholas Maropis as the engineer in charge. Others who cooperated in the research and in the preparation of this report are Carmine F. DePrisco, Chief Electronics Engineer; J. G. Thomas, Metallurgist; and Janet Devine, Physicist. This report has been given the Aeroprojects internal number of RR-61-75.

This is an interim report, and the data reported herein are of a preliminary nature subject to analysis and modification as research progresses.

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PUBLICATION REVIEW

Approved by: J. Byron Jones

J. Byron Jones,
Director of Research

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INTRODUCTION

The increasing use of the newer, high-temperature, corrosion-resistant metals and alloys in missile, space vehicle, and atomic applications has introduced new metal-joining problems that can not be readily solved by conventional techniques. Producing satisfactory bonds in such materials as molybdenum, René 41, Inconel X, and AM-355, in both similar and dissimilar combinations of medium and heavy gages, present certain difficulties.

Since the first technical paper on ultrasonic welding (1)* was published, this subject has received increasing attention at various metallurgical conferences (2-6), as well as from American industry (7-15), especially the metal fabrication industry (16-23), and from foreign investigators (24-29).

Ultrasonic welding equipment already developed and in use has demonstrated its effectiveness in joining various materials of interest to the aerospace industries. Only in some of the aluminum alloys, however, has welding been possible in the heavier sheet gages (up to about 0.090 inch). With the existing equipment, the gage for most other materials is limited to about 0.040 inch. Extension of the utility of the process to heavier and harder materials requires substantial increases in the net vibratory power delivered to the weld zone. Such increases can come via only two avenues:

1. transducer-coupling systems of greater power-handling capacity for welding machines and/or increased efficiency of the transducer-coupling systems

2. increased power to the transducer-coupling system.

The major objective of Phase I of this program is to develop ultrasonic welding equipment adequate for joining the harder, higher strength metals and alloys in thicknesses up to about 0.10 inch. To achieve this objective it will be necessary to establish the feasibility of joining metallic materials, as exemplified by columbium alloy, molybdenum (Mo-0.5 Ti) alloy, tungsten, René 41, AM-355, and Inconel X, in monometallic and dissimilar material combinations and to outline a systematic approach to the development of techniques and equipment necessary to make reliable, reproducible seam and spot-type ultrasonic welds.

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* Numbers in parentheses refer to references listed at end of report.

Determination of equipment requirements for ultrasonically welding metallic materials in a specific thickness range must begin with a study of the energy requirements for making the welds. This is not a matter of merely defining the line power required to operate welding equipment, nor does it deal solely with the more complex problem of the acoustical energy delivered into the weld zone. Actually, the flow of energy through the entire electro-acoustical system must be considered.

Electrical power from a standard power line (60 cycles) is delivered into the "ultrasonic generator" or power source, where it is converted by means of auxiliary electrical equipment, such as electronic oscillators and power amplifiers, into electrical power at the operating frequency of the welding machine. This high-frequency electrical power is delivered to the transducer, which converts it into vibratory power of the same frequency. The power then passes through the coupling system, which may consist of one or more members, into the welding tip and the metal being joined.

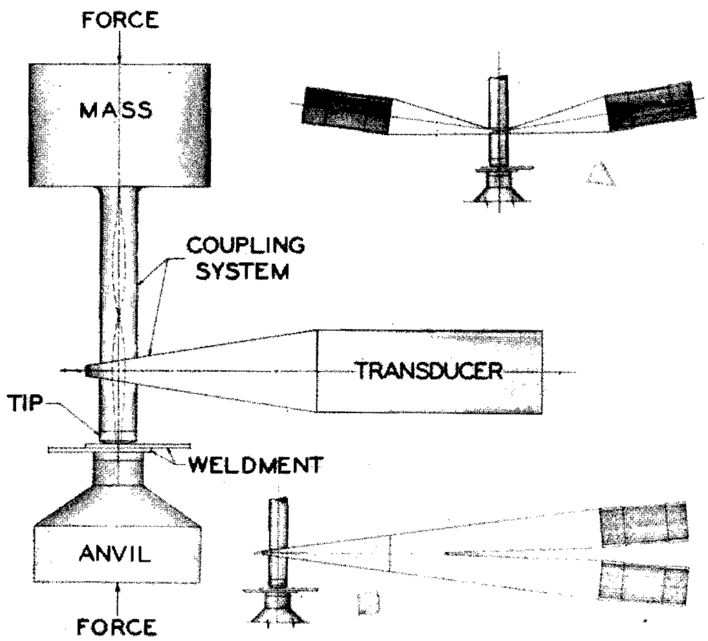
Certain elements are common to transducer-coupling systems for welding, and these require development for effective use in higher power ultrasonic welding machines. Transducer material may be selected from a variety of candidates, and transducer designs depend in large measure on the selected transducer material. Coupling material must be selected with consideration of certain material properties, some of which may not have been quantitatively established. Welding machine tips involve especially difficult requirements.

The basic concepts of these systems consist of a transducer, a coupling system, a welding tip, and an anvil or support for the workpiece. After the most promising system elements are determined, the best potential coupling system must be selected from two general classes and a variety of types.

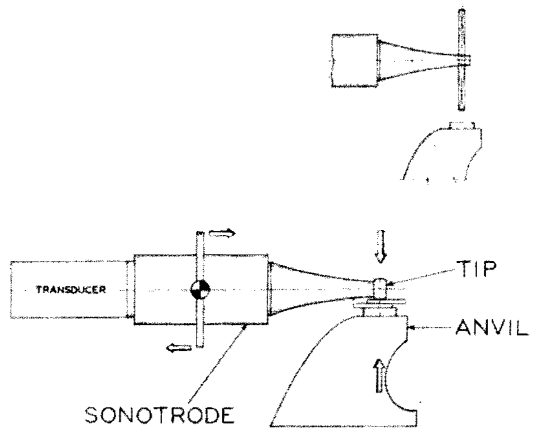
In the wedge-reed system, used in higher power spot-type welders, acoustical energy is delivered to a wedge-shaped member (a mechanical transformer) which executes longitudinal vibration and excites the reed member in flexural vibration at a somewhat greater amplitude than is produced by the transducer, causing the welding tip to vibrate essentially parallel to the weld interface.

Smaller welders and portable-type welders conveniently incorporate the lateral-drive system of Fig. 1. In this case, the tip is attached to a coupler which vibrates longitudinally to produce tip excursion parallel to the weld interface. Clamping force is applied through bending of the coupler.

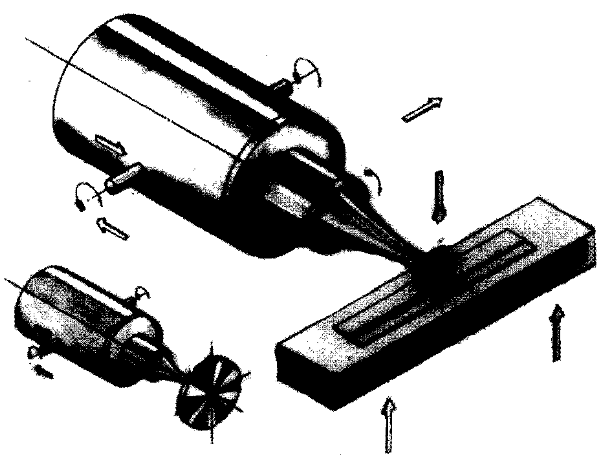
A ring-welding machine is essentially a special kind of spot-type welder that produces an uninterrupted annular weld with a single, short power interval. Such a welder utilizes a torsionally driven coupler system. In



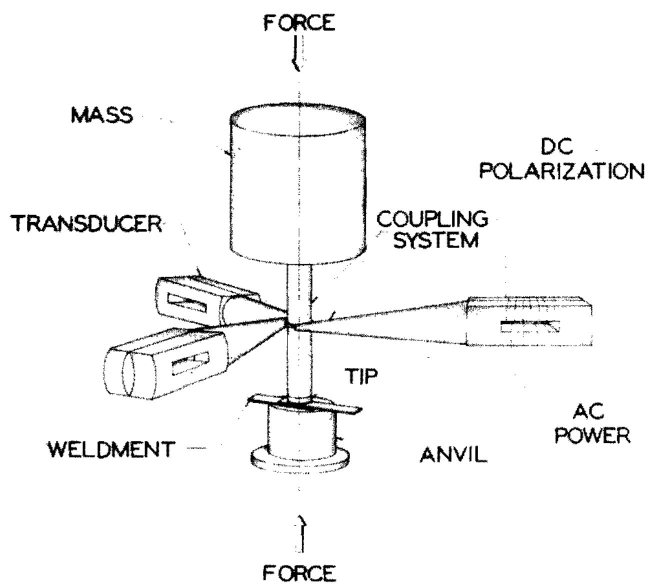
A. WEDGE-REED SYSTEM



B. LATERAL-DRIVE SYSTEM



C. CONTINUOUS-SEAM SYSTEM



D. RING WELDER

Fig. 1: SKETCHES OF TYPICAL ULTRASONIC WELDING SYSTEMS

one type of ring welder arrangement, illustrated in Fig. 1, the longitudinally vibrating "horns" (mechanical transformers) are attached approximately tangent to the torsional reed member, producing torsional displacements of the welding tip. Other arrangements for producing this torsional vibration have also been developed.

A continuous-seam welder incorporates a lateral-drive transducer-coupling system rotating on antifriction bearings with power introduced through slip rings, usually with provision for rotation of the entire transducer-coupling disk-tip system by a motor drive. A disk or ring-like tip operates in synchronous rolling contact with the work so that there is essentially no slippage between the tip and the work.

I. MATERIAL WELDING FEASIBILITY

Establish the feasibility of joining refractory metals and of joining a refractory metal to a dissimilar design material by ultrasonic techniques.

A. Background

This work is concerned with showing the feasibility of ultrasonically welding such refractory metals as tungsten, molybdenum, tantalum, and columbium and such other design materials as the superalloys typified by AM-355 steel and Udimet 700. These materials are relatively new, and their properties are not as well defined as those of such more common metals and alloys as aluminum, copper, and nickel. Consideration will, therefore, be given to a limited number of materials for comprehensive study in the course of this program.

B. Selection of Materials

Manufacturing Technology personnel of the Aeronautical Systems Division of the Air Force Systems Command have recommended the following six materials for the focus of efforts during this program:

1. AM-355 steel 55
2. Inconel X Ni's
3. René 41 Ni's
4. tungsten
5. molybdenum-0.5 titanium alloy Mo
6. columbium alloy (Union Carbide Cb-74 or DuPont D-31). Cb

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C. Properties and Other Pertinent Data of Materials (30-41)

With a view to fitting these specific materials into existing theory regarding ultrasonic welding, as well as to assisting in refining such theory, data on the physical properties of these materials have been assembled in Table 1, data on the mechanical properties are given in Table 2, and certain metallurgical data are reported in Table 3. Additional data will be incorporated into the tables as the program proceeds.

Table 1

SELECTED PHYSICAL PROPERTIES OF WELDMENT MATERIALS

	Multiplier**	Temperature	René 41	Mo-0.5Ti VAC-SR	Tungsten	AM-355 SCT	Inconel X SHT	D-31
			Weldment Material and Condition*					
Density, $lb/in.^3$		Room	0.296	0.368	0.697	0.282	0.298	0.292
Linear Coefficient of Thermal Expansion, in./in.-°F	10^{-6}	Room	6.5	3.1	2.6	6.4	7.6	4.1
		1000°F	7.5	3.2	2.7	7.2	7.7	
Thermal Conductivity, Btu-in./ft^2-hr-°F		Room	63	936	115	104	85	
		1000°F	105	840	90	144	106	
Thermal Diffusivity, ft^2/hr		Room	0.095	2.01	0.249	0.148	0.131	
		1000°F	0.158	1.75				
Specific Heat, Btu/lb-°F		Room	0.108	0.061	0.032	0.120	0.105	0.074
		1000°F		0.063				

* SCT: subzero-cooled and tempered; SHT: solution heat-treated; and VAC: vacuum arc-cast. All material procured in the annealed or stress-relief-annealed condition.

**Compute each item of data with the multiplier indicated for the property.

Table 2

SELECTED MECHANICAL PROPERTIES OF WELDMENT MATERIALS

	Multiplier**	Temperature	Weldment Material and Condition*					
			René 41	Mo-0.5Ti VAC-SR	Tungsten	AM-355 SCT	Inconel X SHT	D-31
Ultimate Tensile Strength, psi		Room	185,000	145,000	120,000	223,000	160,000	100,000
		1000°F	178,000	110,000	75,000	197,000	140,000	68,000
Yield Strength (0.2% offset), psi		Room	140,000	115,000		195,000	120,000	98,000
		1000°F	134,000	100,000	18,000	140,000	83,000	68,000
Elongation, %		Room	20	14	0	10	25	15
		1000°F	13			7	10	5
Poissons Ratio		Room	0.310	0.324	0.284	0.276	0.290	0.380
		1000°F	0.325					
Modulus of Elasticity, psi	10^6	Room	31.6	45.5	59.0	28.7	31.0	16.5
		1000°F	27.3		55.0	24.0	25.0	12.8
Shear Modulus, psi	10^6	Room	12.1	17.4	21.8	11.4	12.0	6.0
		1000°F	10.2			9.4		

* SHT: solution heat-treated; SCT: subzero-cooled and tempered; and VAC: vacuum arc-cast. All material was procured in the annealed or stress-relief-annealed condition.

**Compute each item of data with the multiplier indicated for the property.

Table 3

METALLURGICAL PROPERTIES AND ANTICIPATED WELD-ZONE TEMPERATURES OF VARIOUS WELDMENT MATERIALS

Material Condition*	Mo-0.5Ti VAC	Tungsten	AM-355 SCT	Inconel X SHT	D-31
Crystal Structure	bcc	bcc	**	**	bcc
Recrystallization Temperature, °F	2100	2350-2750			1800-2100
Melting Point, °F	4370	6170	2500	2540	4100
Anticipated Temperature in Weld Zone, °F					
Maximum	2135	2855	1020	1040	1820
Minimum	1360	2270	580	590	1135

* SCT: subzero-cooled and tempered; SHT: solution heat-treated; and VAC: vacuum arc-cast. All material was procured in the annealed or stress-relief-annealed condition.

**Multiphase structure; structure of the matrix in the annealed condition is fcc.

As will be shown later in this report, current theories of ultrasonic welding relate the energy requirement associated with producing spot-type welds to the hardness and thickness of the weldment material. Pertinent data on the welding-energy requirements for the six weldment materials of interest in various thin gages were assembled from the data of previous experimental work and are reported in Table 4.

Available ultrasonic welding data indicate that although meticulous attention to surface preparation is not necessary, oxide-free and degreased surfaces respond more readily to welding. Accordingly, letters requesting information on surface films and their properties, as well as cleaning and surface preparation procedures, have been sent to the research department of each manufacturer from whom metals for this program were purchased. To date, five replies have been received. Additional requests are being transmitted to other material information sources.

Inasmuch as recrystallization of refractory metals and superalloys results in strength degradation of such materials, recrystallization should be avoided. One noteworthy advantage of ultrasonic welding is the absence of a cast structure and, except in unusual cases, of recrystallization.

Recent research shows that the temperature rise commonly observed in ultrasonic welds is in the range of 35%-50% of the homologous melting temperature. In most cases, this is below the temperature at which recrystallization takes place. Other research (42) shows that temperatures during welding can be controlled within limits that are probably adequate to preclude recrystallization.

The recrystallization temperatures, given in Table 3, represent a summary of published data and of expected weld-zone temperatures. Thus, with delineation of suitable welding machine settings, the avoidance of recrystallization appears to be practical.

Table 4

EXPERIMENTAL WELDING DATA AND PREDICTED ENERGY REQUIREMENTS FOR SELECTED WELDMENT MATERIALS

Material and Hardness*	Gage, inch	Previous Experience: Energy, watt-sec	Clamping Force, lb	Typical Weld Tensile Strength, lb	Predicted Energy Required, watt-sec
René 41	0.010	1000	800	350-500	
	.006-.020			260	
Mo-0.5 Ti VMH = 265 to 300	.005	720	300	60	600-900
	.010	1200	400		1200-1650
	.015	2000	400 600	220 100	2000-2800
		2500	600	150	
	.017	3000	600	250	2000-2800
Tungsten VMH = 300	.005	700 510	150 800 900	18 90 100	900
	.010	2600 1920	900 500	75 57	1630
AM-355	.008	180 202 560	350 350 350	380	
Inconel X VMH = 135	.012	500-1000	100	207	610
		450-1000	150	287	
	.020	1500	150	290	1260
	.032			1520	
D-31 VMH = 238	.006	1200	350	38	700
	0.008	3000	700		900

*Vickers microindentation hardness number.

II. WELDING ENERGY CONSIDERATIONS

Study the energy requirements for welding columbium (D-31) alloy, tungsten, molybdenum-0.5% titanium alloy, René 41, AM-355, and Inconel X.

The energy requirements for vibratory welding a variety of materials, including some of the refractory metals, have been studied extensively during the past several years. Appropriate equipment, techniques, and instrumentation were developed for identifying the various critical factors associated with ultrasonic welding energy and for measuring such factors, including temperatures in the weld zone (42-44). Experience and information were accumulated for welding thin gages of refractory metals (such as columbium, molybdenum, tantalum, and tungsten) and of superalloys (such as 17-7 PH, AM-355, J-1500, Inconel X, and René 41).

Since many of the problems encountered in welding such materials have been recognized and variously, though not completely, solved, refinement and extension of this earlier work to the heavier gages of the candidate materials are needed.

A. Predicting Weldability and Power Requirements

On the basis of earlier fundamental ultrasonic-welding research, a first-approximation criterion for determining the weldability of a given material in terms of thickness and acoustical energy was postulated and defined by the equation (45):

$$E = K\, H^{3/2}\, t^{3/2}$$

where E is the acoustical energy in joules (watt-seconds), H is the Vickers microindentation hardness number of the material, t is the thickness of the sheet in inches, and K is a linear constant which incorporates other contributing variables.

Since this energy equation was initially derived from experimental data obtained over a period of time for both common and exotic materials, predicting the weldability of a new material by this means has proved to be reasonably accurate within the thickness range so far studied. For thicker materials, however, modification of the equation may be necessary. Energy requirements for welding up to 0.1-inch-thick refractory material were calculated and are given in Column 3 of Table 5. The relevant acoustical power at various welding intervals is given in Columns 4 through 6 of the table.

Table 5

ESTIMATED ACOUSTICAL ENERGY AND POWER REQUIRED* TO WELD MATERIALS 0.1-INCH THICK IN ANNEALED OR STRESS-RELIEVED CONDITION

			Power Required, kw		
Material	VMH**	Energy Required, kw-sec	At 0.1 sec	At 0.5 sec	At 1.0 sec
René 41	300	10.3	103	21	10
Mo-0.5 Ti	265	9.2	92	18	9.2
Tungsten	300	10.3	103	21	10
AM-355	- - - - - -Not yet available- - - - -				
Inconel X	135	2.9	29	5.8	2.9
D-31	238	7.5	75	15	7.5

* Based on equation: $E = K H^{3/2} t^{3/2}$.

**Vickers microindentation hardness number.

Under certain circumstances, very short welding intervals may be mandatory. When a material has a ductile range at a somewhat elevated temperature, however, the desired result can sometimes be produced with a fairly long interval (such as 1 second) at low power preceding a second short interval at high power.

Considerable data, as well as experience, are required before the power requirements for the materials of interest in this program can be firmly established. As is evident, the power required of the welding equipment will be high when the requisite welding interval is short.

B. Clamping Force Determination

Experience has shown that the minimum power required to produce a good weld is associated with a clamping force which, within certain limits, permits the best impedance match with the weldment. Techniques that have been developed for establishing the best clamping force are described in the following subsections.

1. Threshold-Curve or Nugget-Pullout Method

Clamping force requirements for reasonably malleable materials are established by a method based on weld evaluation by a peel test (42, 46). Welds are made at one clamping force and one welding interval but at decreasing power as long as the welds fail the peel test by nugget pullout. This procedure is repeated at various clamping forces to obtain data for establishing a power:clamping force curve. The minimum of the curve corresponds to the optimum clamping force. This curve may also be used as a threshold curve for welding as it indicates the threshold power, or minimum energy conditions (MEC), for welding.

2. Thermal-Response Method

For brittle materials, the nugget-pullout test is not feasible, so the thermal response (temperature in the weld zone, itself) is used to establish clamping force requirements. For a fixed power setting the temperature in the weld zone, irrespective of weld quality, is approximately maximum at the clamping force associated with the minimum of the power:clamping force curve. Thus, for brittle materials, a convex upward curve of temperature:clamping force can be obtained. With this thermal-response method, it is necessary to ascertain the power setting required to produce a weld at each clamping force, whereas with the nugget-pullout method, the power value is obtained at the same time as is the clamping force level.

3. Standing-Wave-Ratio Method

The power delivered by any ultrasonic transducer-coupling system can be monitored by observing the standing elastic wave ratio existent on the coupler; a standing-wave-ratio method is used to establish clamping-force values at a fixed power setting (42). Microphone-type elements are used to detect the standing-wave pattern along the transmitting system and to measure the ratio of maximum:minimum particle displacement along the acoustic coupler (the associated standing-wave ratio). This is accomplished by applying the electrical signals derived from the microphone elements to the vertical and horizontal deflection plates of an oscilloscope; the result is a varying elliptical pattern, the area of which is proportional to the mechanical power passing through the instrumented portion of the coupler at any instant.

There is also a direct relationship between the thickness of a material and the clamping force necessary to produce an ultrasonic weld at a minimum power level (42). With the clamping force established for a specific thickness of a given material, the best impedance match between the sonotrode tip and the weldment can be obtained so that delivery of energy into the weld area is maximized.

C. Weld-Zone Temperature Measurements

Elevated temperatures in the weld zone may cause recrystallization with consequent degradation of the weldment material. Reliable methods have been developed for measuring weld-zone temperature rise during vibratory welding by meltable-insert and precision single-wire thermocouple insert techniques. Examination of the earlier experimental data thus obtained (46) shows that the temperatures obtained at the weld interface are ordinarily only 35-50% of the absolute melting point of the weldment material. In general, the recrystallization of a metal depends upon its prior conditioning, so the recrystallization temperatures given in Table 6 are intended as representative approximations expressed as percentages of absolute melting points. Although the temperatures shown in the table are at the high end of the 35-50% homologous temperature range, associated with ultrasonic welding, recrystallization of the weldment usually can be avoided by welding at the minimum energy condition.

D. Experimental Equipment

The welding energy requirements for each gage of each material listed in Table 7 will be calculated from the previously discussed energy equation when the Vickers microindentation hardness numbers have been established for all of the materials.

Table 6

COMPARISON OF MELTING POINTS AND RECRYSTALLIZATION TEMPERATURES OF FOUR REFRACTORY METALS

	Melting Point		Recrystallization Temperature		
Material	°C	°K	°C	°K	% of Absolute Melting Point
Mo-0.5 Ti	2625	2898	1100	1373	47
Tungsten	3410	3683	1400	1673	47
D-31 Alloy	2415	2688	1000	1273	47
Tantalum	2996	3269	1300	1573	48

Table 7

MATERIAL* ORDERED FOR PHASE I

Material	Source	Thickness, inch	Quantity, ft^2
René 41	Hamilton Watch Co.	0.008	2
		.020**	
		.030**	
		.040**	
Mo-0.5 Ti	Universal Cyclops	.010	3
		.015	3
		.020	1
		.030	1
Tungsten	Fansteel Metallurgical Corp.	.010	2
		.015	1
		.020	1
		.030	1
AM-355**	Source for thickness range of interest and small quantity required not yet located.		
Inconel X	Whitehead Metals	.010	1
		.020	2
		.031	1
		.043	1
D-31 Alloy	E. I. duPont deNemours & Co.	.010	3
		.015	1-1/2
		0.025	1

* All material procured in the annealed and/or stress-relief-annealed condition.

**Not on hand as of 15 September 1961.

For each material thickness and combinations thereof, a best impedance match into the weldment will be established by the minimum energy condition approach. In order to extend the weldable thickness for each weldment material to the limit of the presently available equipment or of the proposed jury-rigged equipment, a thickness range for each material was estimated on the basis of previous work and on values computed from the energy equation (Table 8).

E. Experimental Procedure

The experimental work follows a well-established pattern beginning with the preparation of materials and proceeding through the determination of welding machine settings, generation of welds, and evaluation of results.

1. Material Inspection and Preparation

Inspection of materials for cracks and other imperfections, which are likely to interfere with the welding process, is particularly important when materials are brittle and, therefore, more susceptible to cracking. Inspection for surface oil, scale, or oxide, which must be removed by suitable chemical or mechanical means prior to welding, is also important.

2. Welding Machine Settings

The requisite welding energy, estimated by means of the energy equation, is used to adjust the power level for welding at weld intervals ranging from 1/2 to 1 second.

Depending on the properties of the weldment material, clamping force at minimum energy condition is ascertained by one of three methods: threshold curves, thermal response (EMF), or standing wave ratio (SWR). The first method is satisfactory for thin, ductile materials but cannot be used with brittle or heavier gage materials. In the present work, with the refractory materials, both the other two methods are satisfactory for establishing clamping-force levels.

3. Weld Evaluations

The weld characteristics are evaluated on the basis of one or more of the following methods: tensile-shear strength determination, cross-tension strength tests, microscopic surface inspection, x-ray inspection of the subsurface, and metallographic study of the weld section and/or progressive planar sections.

end

Table 8

ESTIMATED WELDING ENERGY* FOR AVAILABLE GAGES OF MATERIAL FOR PHASE I INVESTIGATION

Material**	Average VMH*** Value	Gage, inch	Welding Energy*, kw/sec
René 41	300	0.008	0.3
		.020	1.0
		.040	2.0
Mo-0.5 Ti	265	.010	.3
		.015	.6
		.020	1.0
		.030	2.0
Tungsten	300	.010	.3
		.015	.6
		.020	1.0
		.030	2.0
AM-355	Information not available at this time		
Inconel X	135	.020	.3
		.031	.6
		.043	1.0
D-31 Alloy	240	.010	.3
		.015	.6
		0.025	1.0

* Calculated from energy equation.

** All materials procured in annealed and/or stress-relief-annealed condition.

***Vicker's microindentation hardness number.

F. Energy Requirements and Clamping Force

The experimental work for the present program was initiated with 0.010-inch tungsten. The surface inspection for this material failed to reveal any serious imperfections (Table 9), and the test specimens were degreased with Pennsalt A-27 cleaner prior to welding. A laboratory-type instrumented welder, accommodating a standard 2-kw wedge-reed transducer-coupling system and a standard reaction anvil, was used in these first tests.

From the energy equation, about 300 watt-seconds was estimated as the energy required to weld the 0.010-inch material. Accordingly, in scouting tests to establish the proper clamping-force level, the input power was arbitrarily adjusted to somewhat over 300 watts and the weld interval was set at 1 second.

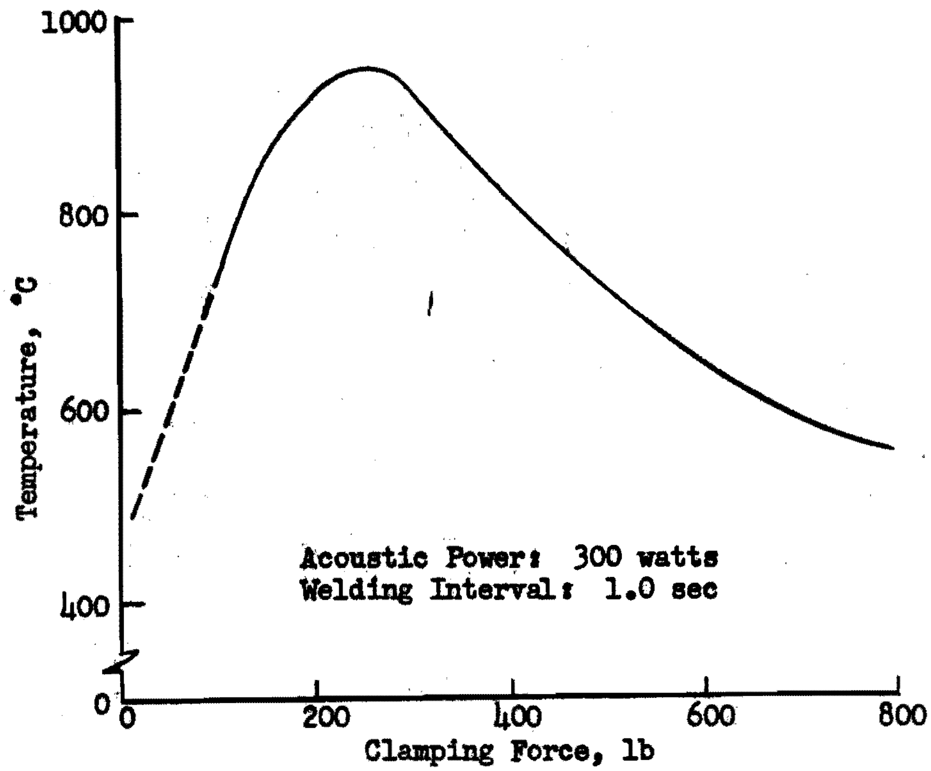
Because of the brittle nature of tungsten, the clamping force for this material was determined by both the weld-zone temperature (by single fine wire, 3-mil Constantan thermocouple) and the standing-wave-ratio techniques; a typical weld-interface-temperature-profile as shown in Fig. 2A, was obtained with the single-wire thermocouple located approximately in the center of the weld. Thermal values are plotted in Fig. 2B, for clamping forces in the range of 100 to 750 pounds--the maximum temperature corresponds to a clamping force of 250 pounds. With the standing-wave-ratio technique, a clamping force of about 300 pounds was indicated by the ellipse area depicted on the oscilloscope. On the basis of these two sets of measurements, the best clamping force for 0.010-inch tungsten appears to be 250 to 300 pounds.

Table 9

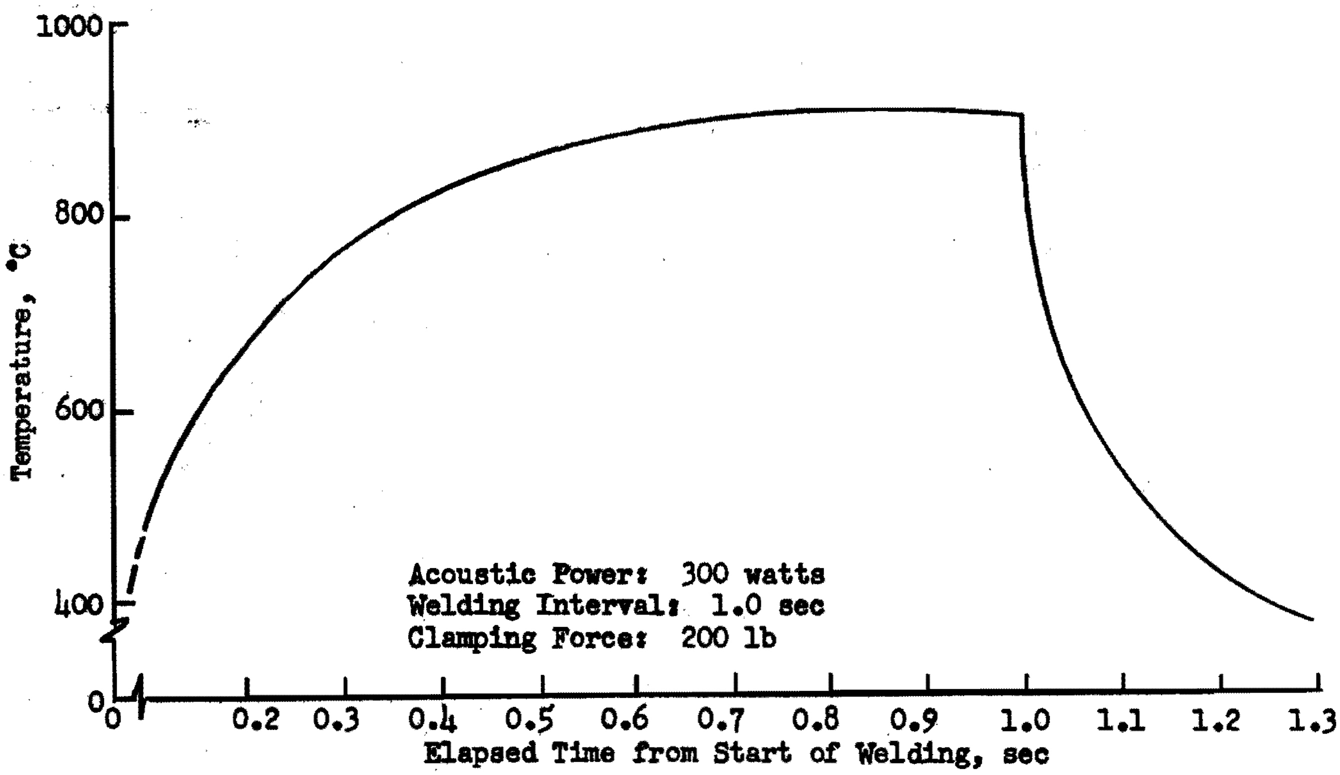
DATA ON SURFACE INSPECTION OF SPECIMENS OF FOUR MATERIALS

General surface over all test specimens was flat, except for D-31 specimens which had wavy surface.

Material	Gage, inch	Surface Roughness, microinches
Mo-0.5 Ti	0.010	15 ± 2
Tungsten	.011	30 ± 3
	.015	15 ± 1
	.020	20 ± 3
	.032	38 ± 3
Inconel X	.020	5 ± 1
	.033	20 ± 2
	.040	25 ± 3
D-31	.005	12 ± 3
	.010	6 ± 1
	.015	11 ± 1
	0.020	4 ± 1



A: VARIATIONS OF WELD-ZONE TEMPERATURE AT DIFFERENT CLAMPING FORCES



B: VARIATION OF WELD-ZONE TEMPERATURE WITH ELAPSED TIME DURING WELDING

Fig. 2: VARIATION OF WELD-ZONE TEMPERATURE AT DIFFERENT CLAMPING FORCES AND WITH ELAPSED TIME DURING WELDING

III. ACOUSTICAL MATERIALS SURVEY

"Survey of current and projected state-of-art materials for their application as transducers and associated equipment with the objective of delivering sufficient power to join the selected materials in thicknesses up to 0.100 inch."

A. Transducer Materials (30, 47-58)

"Transducers and associated equipment" embrace the entire electroacoustical system from the connections for electrical energy input to the point of vibratory energy output, the locale where the transducer-coupling system contacts the area of weld generation.

During recent years, a wide variety of magnetostrictive materials have been evaluated and used in experimental and production-type ultrasonic welding arrays; these include 2V Permendur, Alfenol, "A" nickel, and nickel-cobalt (204) alloy. Such materials have a lower efficiency than some of the electrostrictive ceramics; however, with metallurgical methods such as brazing, rugged and durable systems that are relatively insensitive to overloading can be built.

Furthermore, such systems can be operated without permanent damage at temperatures much higher than could be tolerated by any ceramic available until recently. Nickel has been the most effective and widely used of the magnetostrictive materials. Most ultrasonic welding equipment incorporates laminated stacks of thin, annealed "A" nickel sheets which are satisfactory for heavy-duty, continuous operation.

The electrostrictive barium titanate ceramic, currently used in certain types of ultrasonic equipment, dates back to about 1950 when the material was extensively investigated and used in ultrasonic arrays for solid-state metal treatment. Since that time, barium titanate has been used in ultrasonic arrays for various purposes. While its electromechanical conversion efficiency is higher than that of magnetostrictive materials, it has not been used extensively in production-type ultrasonic welding equipment because ceramic transducers of this type are fragile and somewhat difficult to install in coupling systems on a practical basis. Furthermore, its low Curie point (approximately 115°C) introduces a major cooling problem -- overheating must be prevented to avoid depolarization.

Recently, effort has been directed toward the development of new ceramic materials which will withstand high temperatures. These newer ceramics include such family groups as titanates, niobates, tantalates, and zirconates. One of the most promising of the new materials is lead zirconate titanate, which has a reported Curie temperature of about 340°C and a high electromechanical coupling coefficient. Large-size transducers have been fabricated from this material (designated Brush Type PZT-4 and PZT-5) and evaluated.

In order to bring the transducer problems into sharp focus, available data on magnetostrictive and electrostrictive types have been compiled or calculated and are summarized in Table 10. Of immediate interest, is the electromechanical coupling coefficient, the reported power-handling capacity, Curie temperature, thermal conductivity, and diffusivity data.

The electromechanical coupling coefficient serves as an index of how closely the electrical and mechanical portions of the transducer are coupled. The higher this coupling is, the less important does the precise tuning of a system become and the higher the resulting transduction efficiency. Losses associated with conversion of the stored mechanical energy to the "delivered" vibratory energy, however, are not included in the electromechanical coupling coefficient. The power-handling capacity, based on data from various sources, refers to various candidate units under continuous-duty operation with only moderate cooling. The thermal characteristics are of importance because they set limiting conditions on the factors mentioned. The Curie temperature cannot be exceeded without temporary (for magnetostrictive) or permanent (for electrostrictive) damage to the transducer.

B. Coupler Materials (30, 59-67)

Parallel with evaluation of transducer materials over the past years, continuing studies of candidate coupler materials have been carried out, and the problems involved in the selection of coupler materials for specific applications have been recognized.

Couplers for ultrasonic welding systems ordinarily do not have difficult high temperature restrictions, so the requirements are fairly straightforward. Primarily, the coupler must be made of a material which will transmit high cyclic elastic forces with low energy losses in the frequency range of interest. In addition, the material must have engineering practicability, that is, must be capable of sustaining the static loads imposed on it, must be readily available in suitable sizes, should be easily fabricated, and almost certainly must be metallurgically joinable (weldable or brazable).

The background, which serves as the basis of this survey has included studies, sometimes cursory and sometimes in depth, of such materials

Table 10

PROPERTIES OF TRANSDUCER MATERIALS

		Electrostrictive				Magnetostrictive			
		Lead Titanate Zirconate		Barium Titanate	Lead Metaniobate	Nickel		2V Permendur	Alfenol
	Multiplier*	PZT-4	PZT-5			"A"	(204)		
Electromechanical Coupling Coefficient (k_{33})		0.674**	0.675	0.50***	0.40	0.31 0.30-.35	0.51 0.50-.60	0.27 0.23-.30	0.27 0.27-.29
Reported Power-Handling Capacity, watts/m²#	10^4	15		12		8	9	12	
Piezoelectric Strain Constant, m/volt	10^{-12}	256	320	150	90				
Magnetostrictive Stress Constant (λ), newtons/weber	10^6					16.7-20	32		6.7
Curie Temperature, (°C)		340	340	120	500	360	410	525	500
Density (ρ), kg/m³	10^3	7.5	7.5	5.5	5.9	8.89	8.9	8.15	6.7
Velocity of Sound (c), m/sec		3960	3780	5680	3125	4780	4790	5260	4500
Characteristic Specific Impedance (Z_ℓ), kg/m²-sec	10^7	2.97	2.83	2.75	1.84	4.36	4.30	4.30	3.02
Specific Heat, kcal/kg-°C		0.10	0.10	0.12		0.13	0.13		
Thermal Conductivity (K) (kcal-m)/m²-sec-°C	10^{-3}	0.30	0.30	0.60		14.5	12.1		
Thermal Diffusivity (α), m²/sec	10^{-6}	0.40		0.91		12.5	10.5		
Linear Coefficient of Thermal Expansion (isotropic), m/(m-°C)	10^{-5}	0.22-.40	0.22	1.9		1.33	1.33	0.95	
Driving Impedance		- - -Intermediate##- - -				Adjusted by controlling number of coil turns			
Practical Joining Methods		- - -Adhesives or Mechanical- - -				- - - - - - - -Brazing- - - - - - -			

* Multiply each item of data by multiplier indicated for the property. **100°C. ***75°C.

\# Determined for continuous operation with only moderate cooling.

\##Drive voltage (E) is in range of 500-1000 volts/mm thickness of ceramic.

as titanium, aluminum, R Monel, K Monel, and, recently, aluminum bronze. The practical application is interesting; for example, the replacement of a steel coupler with one made of K Monel in one type of seam-welding unit permitted an increase of up to 2 gages in the thickness of the material that could be effectively welded at a constant electrical energy input, primarily because the coupler material did not seriously attenuate acoustic energy in the operating frequency range of the machine.

Titanium may be an effective coupler material, since it has a very high "Q"* at high strain levels and, accordingly, transmits vibratory energy with relatively little attenuation. In order to bring the problem of coupling materials into perspective, relevant data for coupler materials presently being considered are summarized in Tables 11, 12, and 13.

The path of vibratory energy is from the transducer through the intermediate coupling elements to the terminal element or welding tip and ultimately to the weld interface. As indicated earlier, the transmission of this energy is not straightforward, and careful attention to material properties and acoustical design detail is necessary throughout the entire transmission system.

Maximum power transmission can occur only when the impedances of the component elements are properly matched at their junctions, and the components are made of material that transmits vibratory energy with minimum attenuation. Under idealized conditions, no standing waves exist in the coupling system, and, therefore, all parts of the system are subject to the same cyclic strain and maximum power delivery. As stated previously, ideally the impedance at the junctions between the various components of the transducer-coupling system should match, but in practice this can not always be accomplished (as, for example, at the wedge-reed joint in a wedge-reed spot-type welder).

Table 14 shows the percentage of energy transmitted across the interface between the indicated transducer and coupler materials. This is determined for the case of equal areas from the equation:

$$T = \left[1 - \left(\frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}\right)^2\right] \times 100,$$

where T = the percentage of incident energy transmitted across the interface

$\rho_1 c_1$ = the specific acoustic impedance of one material (ρ = density, c = thin rod sound velocity)

$\rho_2 c_2$ = the specific acoustic impedance of the second material (68).

*"Q" is 2π times the ratio of the total stored energy at resonance to the average energy dissipated per cycle.

Table 11

PHYSICAL AND MECHANICAL PROPERTIES (AT ROOM TEMPERATURE) OF CANDIDATE COUPLER MATERIALS

	Multiply by*	Aluminum Bronze	Beryllium Copper	Inconel X	K Monel	Stainless Steel (Series 300)	Steel (Carpenter 883)	Titanium (6Al-4V)
			Physical Properties					
Density (ρ), kg/m^3	10^3	7.60	8.23	8.51	8.46	7.90	7.84	4.43
Linear Coefficient of Thermal Expansion, m/(m-°C)	10^{-5}	1.62	1.67	1.37	1.44	1.73	1.10	0.95
Thermal Conductivity (K), (kcal-m)/(m^2-sec-°C)	10^{-3}	14.7	13.7	3.0	4.2	3.8	6.7	1.7
Thermal Diffusivity (α)**, m^2/sec	10^{-6}	21.5	16.6	3.2	3.9	4.0	7.7	2.9
			Mechanical Properties					
Young's Modulus (E), newtons/m^2	10^{10}	10.7	11.7	21.4	17.3	19.3	20.4	11.4
Shear Modulus (μ) newtons/m^2	10^{10}	4.0	4.3	8.3	6.6	7.5	7.8	4.3
Ultimate Tensile Strength, newtons/m^2	10^8	6.2-6.6	4.1-5.9	11.5	6.2-7.6	6.2	7.2	9.4
Yield Strength (0.2% offset), newtons/m^2	10^8	3	1.4-6.5	6.2	2.7-4.1	2.4	4.7	8.9

* Multiply each item of data by the multiplier indicated for the property.

** $\alpha = K/\rho S$, where S = specific heat.

Table 12

ACOUSTIC PROPERTIES OF CANDIDATE COUPLER MATERIALS

	Multiply by*	Aluminum Bronze	Beryllium Copper	Inconel X	K Monel	Stainless Steel (Series 300)	Steel (Carpenter 883)	Titanium (6Al-4V)
Young's Modulus (E), newtons/m^2	10^{10}	10.7	11.7	21.4	17.3	19.3	20.4	11.4
Shear Modulus (μ) newtons/m^2	10^{10}	4.0	4.3	8.3	6.6	7.5	7.8	4.3
Poisson's Ratio (σ)		0.350	0.350	0.290	0.320	0.285	0.300	0.340
Velocity, m/sec								
Shear Velocity (c_s)**		2280	2310	3110	2760	3140	3160	3100
Rod Velocity (c_ℓ)***		3750	3800	5000	4480	5030	5100	5076
Impedance, kg/sec-m^2	10^7							
Shear (Z_s)**		1.73	1.90	2.65	2.33	2.48	2.47	1.37
Characteristic Specific (Z_ℓ)**		2.85	3.12	4.25	3.79	3.97	3.98	2.25

* Multiply each item of data by the multiplier indicated for the property.

** $C_s = \sqrt{\mu/\rho}$ and c_ℓ = E/ρ; c_ℓ represents longitudinal or thin rod velocity.

*** $Z_s = \sqrt{\mu\rho}$ and $Z_\ell = \sqrt{E\rho}$.

Table 13

MACHINING AND JOINING CHARACTERISTICS*
OF CANDIDATE COUPLER MATERIALS

Coupler Material	Machining	Welding **	Brazing	References
Aluminum Bronze	1	1	1	62
Beryllium Copper	1	1	1	30
Inconel X	1	1	1	30, 63
K Monel	2	1	2	65
Stainless Steel (300 Series)	1	1	1	30
Steel (Carpenter 883)	1	1	1	30
Titanium (6Al-4V)	2	2		30

* 1: Not difficult, satisfactory
  2: Somewhat difficult.

**Data concerning the performance of welded joints are not available.

Table 14

IMPEDANCE MATCHING BETWEEN CANDIDATE COUPLER AND TRANSDUCER MATERIALS

Coupler Material	Z_ℓ	% Transmission Across Interface Between Indicated Coupler and Transducer Materials — Transducer Materials and Longitudinal Impedance (Z_ℓ), 10^7 (kg/sec-m2) — Lead Titanate Zirconate: PZT-4 2.97	Lead Titanate Zirconate: PZT-5 2.83	Barium Titanate 2.75	Nickel: "A" 4.36	Nickel: (204) 4.30
Aluminum Bronze	2.85	99.2	100.0	100.0	95.6	95.9
Beryllium Copper	3.12	99.4	99.8	99.7	97.3	97.5
Inconel X	4.25	96.8	96.0	95.8	100.0	100.0
K Monel	3.79	98.5	97.9	97.7	99.5	99.6
Stainless Steel (Series 300)	3.97	97.9	97.2	97.0	99.8	99.8
Steel (Carpenter 883)	3.98	97.7	97.2	97.0	99.8	99.8
Titanium (6Al-4V)	2.25	98.1	98.7	98.8	89.8	90.4

Recent theoretical considerations (46) indicate that the power that can be transmitted by any elastic system is defined by the equation:

$$P_m = \frac{1}{2} A \frac{\sigma_m^2}{\sqrt{E\rho}}$$

where P_m = the maximum power

A = the cross-sectional area of the coupler or wave guide

σ_m = the maximum allowable stress

E = the elastic (Young's) modulus for the material of which the coupling member is made

ρ = the density of this material.

The maximum power that can be delivered by a transducer-coupling system for welding appears to be independent of frequency *per se*, but it does depend upon the mechanical and physical properties of the materials of which the system is made. Here σ_m represents the maximum allowable stress and $\sqrt{E\rho}$ represents the characteristic specific impedance for the material. Thus, it appears that the ratio $\sigma_m^2/\sqrt{E\rho}$ is a figure of merit for the potential of any material for use as an acoustic transmitter in high powered applications.

Further theoretical considerations (in Appendix) carried out in part during a previous study (45) compared the strain-energy density associated with the various vibratory modes which are summarized in Table 15. These data indicate that the ratio of the maximum strain energy to material density, $\mathcal{E}_m/\rho$, is another way of expressing a figure of merit for elastic materials.

Application of Hooke's law and simple algebraic manipulation show that the earlier figure of merit is equivalent to $\mathcal{E}_m/\rho$ multiplied by the characteristic impedance of the material. Thus, it is clear that either ratio

$$\frac{\sigma_m^2}{\sqrt{E\rho}} \quad \text{or} \quad \frac{\mathcal{E}_m}{\rho}$$

can serve as a useful guide in any preliminary screening for candidate materials.

The mechanism by which energy is dissipated in the metal coupling members is usually termed internal friction (69). For our application it is desirable that the coupler material offer minimum internal friction to the transmission of vibratory energy in the frequency range of interest.

Table 15

TYPICAL PHYSICAL AND MECHANICAL PROPERTIES
OF CANDIDATE TIP MATERIALS

	Multiplier*	Steel			Inconel X	K Monel	René 41	Astroloy	Molybdenum	Mo-0.5Ti
		M-2	T-2	4340						
Physical Properties										
Density (ρ), lb/in^3	–	0.293	0.312	0.280	0.298	0.304	0.296	0.287	0.369	0.368
Linear Coefficient of Thermal Expansion, in./(in.-°F)	10^{-6}			6.2	7.6	8.0	6.5		2.7	3.1
Thermal Conductivity (K), (Btu-in.)/ft^2-hr-°F					85	122	63		936	936
Thermal Diffusivity (α), ft^2/hr					0.131	0.152	0.095		1.94	2.01
Specific Heat (S), Btu/(lb-°F)				0.115	0.105	0.127	0.108		0.063	0.061
Mechanical Properties										
Young's Modulus, psi	10^6			31	25.1	31.6			46	46
Tensile Strength, psi				191,000	162,000	140,000	160,000	194,000	102,200	132,000
Yield Strength (0.2% offset), psi				180,000	92,000	100,000	120,000	142,000	78,800	99,500
Poissons Ratio					0.290	0.320	0.310		0.310	0.310
Rockwell C Hardness Range		62-66	61-66	41	20-28	21-28				

* Multiply each item of data by the indicated multiplier.

In summary, coupling components should:

1. be easily fabricated using standard machine tools

2. be easily joined; metallurgical attachment is most desirable, and for very high power properly matched systems, it is probably mandatory

3. have good fatigue life

4. be compatible in characteristic specific impedance to the transducer and terminal elements; that is, its characteristic impedance must not be too different from the impedance of the other components.

5. exhibit low internal friction at high strain levels and, therefore, deliver energy with minimum attenuation.

The available information in these categories for materials now being considered for couplers is included in these summary tables.

C. Tip Materials (22, 30, 31, 34, 64, 67, 70)

During the delivery of vibratory energy to the weldment, the terminal tip of the sonotrode is subjected to high dynamic stresses and elevated temperatures for short time periods -- these conditions can quickly damage a tip. The relationship of tip performance to the dynamic stress distribution associated with the tip-weldment interface (46) and to the physical characteristics of various tip materials has been considered previously.

Ordinary tool steels provide satisfactory performance and life in welding aluminum or copper alloys, while Inconel X is satisfactory for welding mild steels, titanium, zirconium, and similar alloys. In welding high-strength, high-temperature, and hard, brittle metals and alloys, the life of the tool steel tips so far used have been short; Inconel X in the heat-treated and aged condition provides a substantial improvement. Type 301 stainless steel can be welded with a wide range of tip materials, while AM-355 steel is more critical. Evaluation of several tip materials showed only Inconel X to have a reasonable tip life in welding this material.

The relatively new nickel alloy, Astroloy*, with superior high-temperature properties, exhibited extended life and good welding characteristics in joining several high-strength, high-temperature alloys.

Several kinds of spot-type welding tips have been investigated (Section V of this report). Examples are a full tip, silver-brazed to the coupler, and a tapered insert tip which is used for certain materials that are obtainable in only rod configuration, cannot be readily brazed, or are too brittle for unsupported use. Previous evaluation studies have included

* Product of the General Electric Company.

full tips of tool steel, Inconel X, molybdenum-0.5 titanium, Nitroloy, and other metals and have included inserts of tool steel, tungsten carbide, titanium carbide, K Monel, and austenitic manganese steel. Some of these materials were found to crack under high loads, some eroded readily and required frequent redressing, and some exhibited excessive sticking to the weldment.

Information, regarding the various welder-tip designs, is summarized in Tables 17 and 18 in Section V. The tip material must be tough and resistant to wear so that the tip does not deform, spall, erode, or crack when high vibratory power is applied; also, satisfactory physical properties must be retained at elevated temperatures which depend upon the materials being welded. Tip materials with good thermal conductivity are desirable because liquid cooling of spot-type welding-machine tips has already become a standard machine feature.

However, in the final analysis, tip materials must be tested under actual welding conditions before a proper evaluation can be made. Accordingly, performance data for the more promising tip materials will be obtained and reported as this program proceeds.

Information concerning the physical and mechanical properties of promising materials for the fabrication of sonotrode tips and disks, is summarized in Table 15. At the present time, this information is incomplete, but additional information is expected from replies to our letters of inquiry.

IV. ACOUSTICAL MATERIALS STUDY

Determine the material or combination of materials for the transducer and associate equipment most efficient in producing a distortion-free solid-state bond.

A. Transducers

The suitability of candidate transducer materials for use in ultrasonic welding equipment is being evaluated on a basis that reasonably approximates the end use. With spot-type welding equipment, the transducer receives a pulse of electrical energy ordinarily of less than 1-second duration. In roller-seam-type equipment the energy is applied continuously. In spot-type welding the transducer may have a relatively easy duty cycle in which its thermal inertia permits the acceptance of high power levels. In continuous-seam welding, steady-state conditions are likely to prevail so that transducer cooling exercises a strong influence on the energy which the system will handle.

The energy requirements for welding the refractory materials of interest in this investigation were estimated on the basis of the energy equation (discussed more fully in Section II) and by extrapolation from previously obtained data for these or similar materials. These energy requirements will be refined from time to time on the basis of experimental data obtained, as the work proceeds.

Transducers are routinely evaluated (71) by obtaining a motional impedance loop, the data of which defines the resonant frequency of the transducer, the "Q" of the transducer and the potential transducer efficiency. Such loop data are ordinarily secured by means of impedance bridges equipped with oscillators and detectors. The motional-impedance loop, however, is generally ascertained at instrument power levels. Previous experience (42) has shown that transducers can be evaluated for purposes of interest by a direct calorimetric technique which can provide important ancillary information. The transducer is attached to a coupling member in a manner essentially the same as it is attached to a welding machine. The coupling member, is connected directly into an energy absorber such as a large block of lead (Fig. 3), in which a cooling coil carries away the vibratory energy which is degraded to heat in the lead billet.

It will be appreciated that the calorimetric method permits driving the transducers at elevated power levels which can be either pulsed power as

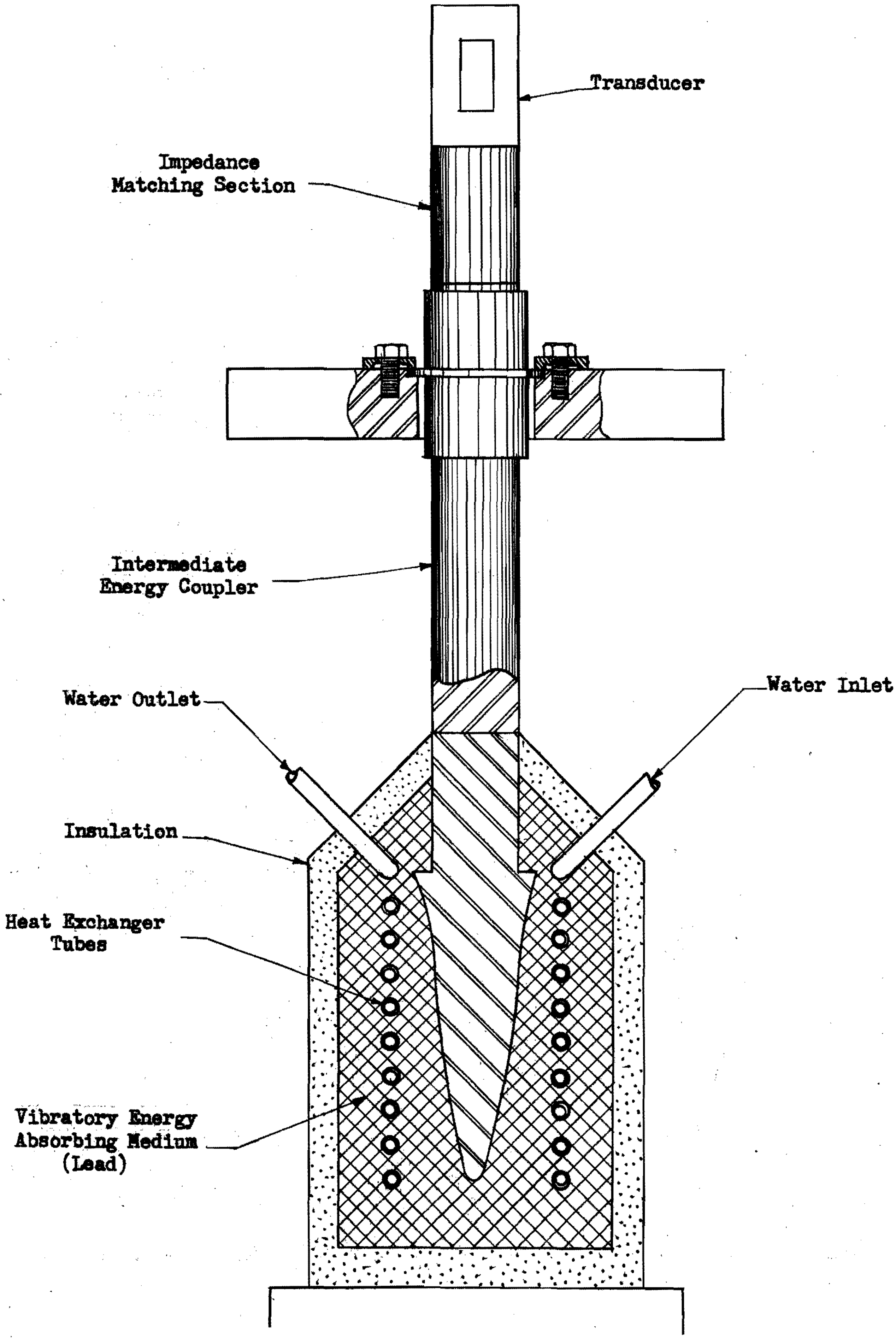


Fig. 3: CALORIMETRIC TEST SCHEME FOR TRANSDUCER AND COUPLER EVALUATION

required for spot-type welding systems or continuous power as is necessary for continuous-roller-seam welding equipment. Moreover, problems of transducer cooling can be studied; in the interval covered by this report, the evaluation system shown in Fig. 3 was designed and partly fabricated. It is expected that this system will be in use to evaluate transducer materials prior to the end of September. Information will be developed on the better-known candidate materials first, particularly lead zirconate titanate, the electrostrictive PZT-4 from Brush Development Company, and the magnetostrictive nickel cobalt alloy from International Nickel Company. Basic information on standard "A" nickel will be obtained. Information on the over-all efficiency of these materials under powered conditions which approximate end use in ultrasonic welding should be shortly available.

B. Couplers

As described in Section III, a coupling member which intervenes between the transducer and the point of energy delivery into the weldment presents three distinct problems:

First: It involves energy losses due to reflections at the transducer-coupler interface and at other junctions or discontinuities between the transducer and the point of energy delivery. Reflection losses at such junctions are minimized when the acoustical properties of each material are about the same, as reported in Table 11.

Second: Losses occur in a coupling member as a result of elastic hysteresis (that is, internal friction); such losses are affected by both power level and frequency, with greater losses occurring at high power levels and frequencies.

Third: If the coupling member conducts vibratory energy at a sufficiently high-power level, or if the standing wave ratio in the system is large and a high-power level is involved, ordinary fatigue failure can (and, indeed, does) occur. When the standing-wave ratio approaches unity, however, a low-carbon steel bar conducts vibratory energy comparable to the electrical energy carried in a copper conductor (upwards of 10,000-12,000 watts/cm^2). This energy range can drop as low as 100 watt/cm^2, however, when the standing-wave ratio is high. Therefore, it is exceedingly important that a coupling system be designed to minimize reflection and transmission losses and to utilize materials with outstandingly good mechanical properties in order to maximize the energy delivered to the weldment. All these factors are difficult to obtain in a single material; in fact, little is known about the transmission and the fatigue properties in the frequency range and at the vibratory energy level that is implicit in ultrasonic welding equipment design.

As reported by Mason (48) such information can be obtained by carrying out certain measurements involving acoustical velocity transformer elements. More recently, Neppiras (72) developed a technique for studying

materials of interest in high-power ultrasonic transmission investigation. With the Neppiras method, both internal energy losses and fatigue strength can be determined.

With the standing-wave-ratio method of energy measurements, which adds an important factor of control to the Neppiras evaluation technique, reasonably straightforward determinations can be made under reproducible conditions in a relatively short period of time.

During the interval covered by this report, equipment has been devised in accordance with Neppiras' technique, and partially assembled.

C. Tips

1. Spot-Type Tips

Spot-type tips are used to produce repetitive welds in a given material or combination of materials. In this system, the sonotrode tip serves two purposes, the most important of which concerns delivery of the energy to the weld zone. Secondly, the tip provides a terminus to the acoustic system. For reasons discussed previously, the material selected for the sonotrode tip must be tough, resistant to wear and match the impedance of the weldment as closely as possible.

The effect of coupling between the tip and the weldment, as influenced by materials, frictional characteristics, etc., has not been investigated. A variety of materials have been welded, however, with big differences between the physical and mechanical properties of the tip and weldment materials. For instance, aluminum alloys and low-carbon and stainless steels, as well as other engineering materials, have been welded successfully with tool steel and nickel alloy sonotrode tips. Furthermore, coupling can be frictional, as in spot-type welding of sheet material, or by positive drive, as in the welding of joint geometries that permit mechanical locking between the tip and the weldment. A high modulus, toughness, and resistance to wear are required properties for resistance (frictional) coupling tips, while in the positive-drive arrangement, the major requirement is adequate mechanical strength to support the expected static and dynamic stresses.

2. Continuous-Seam or Roller Tips

The basic requirements of roller or continuous-seam tips are almost the same as those of the spot-type tips. Roller tips, however, are of two types, resonant and nonresonant. The nonresonant-type tip serves, as in the spot units, as a terminus to the acoustic system and is subjected to only the dynamic shear and normal stresses attendant to the energy delivery into the weldment. The resonant tip serves a dual role of delivering the energy to the weldment and of functioning as a matching transformer between the acoustic system and the weldment. Thus, the rollers may be subjected to the dynamic vibratory stresses associated with component resonance and to those stresses at the junction to the weldment associated with energy delivery to the weld.

The life of roller tips is evaluated in terms of producing seam welds of uniform quality. Tip life can be considerably improved by geometric considerations insofar as these govern the surface fibre stress for a given disk deflection. Inasmuch as the power delivered is proportional to the square of the displacement, and inasmuch as the disk fibre stresses vary as the cube of the disk deflection with respect to the neutral plane, material properties become even more important. Disk materials must possess high strength, extended fatigue life, and compatible coupling and impedance characteristics.

The criticality of these components, as demonstrated during the evolution of the welding process, has been indicated. The suitability of the various materials for power-handling capacity, vibratory energy transmission characteristics, impedance matching characteristics, and fabrication and joining adaptability can be ascertained by measurements and tests. No simple measurement, however, is immediately available for screening purposes, and reliance must be placed, at least temporarily, on standing-wave-ratio measurements to evaluate energy delivery by any unit at constant input conditions and on weld quality. Obviously, this is quite a laborious process, and only a limited number of candidate tip materials can be studied.

V. ENERGY DELIVERY METHODS

Determine the most efficient methods of supplying vibratory energy to the bond interface.

A. Systems

A variety of ultrasonic welding arrays for spot-type, roller-seam, and ring-welding systems have been developed, but details of the specific advantages and disadvantages remain to be defined.

In general, there are two broad classes of systems which are independent of the weld geometry. The first embraces all those types in which a reaction element, or anvil, supports the work pieces and resists compliance thereof with the vibratory forces exerted by the powered sonotrode. The second or "opposition-drive" class comprises systems wherein vibratory energy is delivered to both sides or members of the weldment -- no massive reactive element such as an anvil is involved.

The class of welders having the reaction element includes the wedge-reed design in which the reed is excited by a single coupler element (wedge-type) or by two diametrically opposed couplers operating in opposition (Fig. 1A of p. 3), thus effectively doubling the power capacity. This category also includes the lateral-drive coupler system (Fig. 1B), the roller system (Fig. 1C), and the torsional system (Fig. 1D).

Precise relative efficiencies of the wedge-reed, the lateral drive, and the ring-welding systems have not been established, although much data have been obtained previously with all three types. In general, the wedge-reed system has been used with higher power equipment and the lateral-drive with lower power arrays. The higher bending loads which are associated with the application of clamping force to heavier, harder materials limits the standard lateral-drive system because of such second-order effects as "tip bounce" unless special provisions are provided to preclude them.

To consider the potential efficiency of various types of spot-welder systems, a theoretical analysis relating the strain energy density to amplitude for the longitudinal and flexural cases, previously carried out, was extended to include the torsional concept (in Appendix). This more complete analysis indicates that torsional and longitudinal modes are comparable in power-handling capacity (Table 16), whereas the lateral or bending mode involves greater stresses at similar amplitudes.

Table 16

RELATIONSHIP BETWEEN RELATIVE STRAIN ENERGY LEVELS FOR CONSTANT AMPLITUDE AND RELATIVE AMPLITUDE FOR CONSTANT STRAIN ENERGY LEVELS

Mode of Vibration	Constant Amplitude, Relative Strain Energy Density	Constant Strain Energy Density, Relative Amplitude at End
Longitudinal	1.0	1.0
Lateral:		
Round	2.4	0.65
Rectangular	1.8	0.75
Torsional	1.0	1.0
Flexural (disk)	5.1	0.45

In existing welders of significant power-handling capacity, the reaction element or anvil is a potential source of energy loss because of the energy which passes through and beyond the weld zone. To minimize these losses, considerable effort has been devoted to anvil development. As a result of this past work, isolation systems for anvils have been developed and are now in day-to-day use.

On the basis of the information of Table 5, it is anticipated that acoustical power up to about 25 kw, and possibly higher, will be required to join the candidate materials in thicknesses up to 0.1 inch, and that power levels of this order will almost necessarily be delivered via both of the clamping sonotrodes.

The opposition-drive class of system does indeed, eliminate the necessity for a massive, noncompliant anvil and the problems that are entailed. Such systems have been developed and utilized successfully. However, unless the design of an opposition-drive system incorporates solutions to problems peculiar thereto, it is possible that the energy losses will be greater than those experienced with the reaction-sheet type. For example, a slight shifting of phase in the tip excursion of either sonotrode (from the 180° out-of-phase condition that must prevail) will abruptly produce a great decrease of energy delivery. As a matter of fact, under certain circumstances one transducer coupling system may act as an alternator with the opposing system acting as a motor so that almost no work will be done at the weld locale.

There are at least three avenues to satisfactory opposition-drive operation which have previously been investigated and developed:

1. mechanical intercoupling in which all the transducers drive a common coupler, and the energy output of the coupler is divided by means of a locked mechanical out-of-phase system to provide 180° out-of-phase displacement to the sonotrode tip

2. electrical intercoupling which involves standing-wave-ratio or other monitoring equipment on each coupler or tip for detecting and automatically maintaining the proper phase relationship by a servotechnique

3. electromechanical intercoupling which utilizes a combination of these techniques.

Some experimentation is still required to select the best of these two classes and also to evaluate the practicality of the types of transducer-coupling systems for use in heavy-duty equipment.

In previous studies on this problem, available equipment was jury-rigged to operate at relatively high powers (up to about 6000-8000 watts of high-frequency power to the transducer) without regard to the practicability of ultimate use in heavy-duty equipment. A refined approach is now being prepared to obtain additional information on the opposition-drive class of system.

The possibility that ring welds may be more desirable than standard spot-type welds is also being considered. In any spot-type weld, the structural load is carried from one side of the weldment to the other, generally through the periphery of the spot. The center of the spot contributes little to the spot strength. Nevertheless, with the ordinary ultrasonic spot-type welder, energy is used to produce the interfacial disturbance over the entire weld area, including the center. A ring weld has the promising structural advantage of a bond generated only where it is useful, at the periphery. The ring configuration can be adjusted to provide not only a large bonded area, but also a large-diameter, more efficient weld.

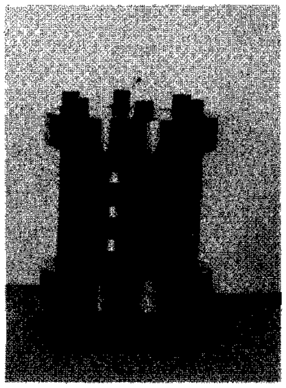
B. Components

1. Transducers

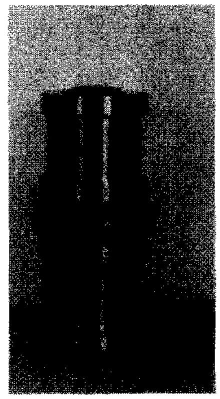
On the basis of information compiled to date, it appears that transducers for welding will involve either magnetostrictive laminated-sheet metal stacks or such ceramic-type materials as lead zirconate titanate. Much experience has been accumulated with the design, fabrication, and service life of such magnetostrictive materials as "A" nickel and nickel-cobalt alloy. So far as is known, little, if any, experience has been obtained with high-power ceramic transducers capable of sustained energy delivery via metal couplers. In order to obtain practical verification of the reported theoretical performance of such ceramic materials in large transducers for extended operation, certain designs for such transducers, evolved prior to this work, have been partially evaluated (Fig. 4).

Loading to maintain the ceramic elements in a state of compression is variously applied. In Fig. 4A, peripherally located tie bolts produce this compressive loading via end plates. In Fig. 4B, a center tie bolt serves the same purpose, while in Fig. 4C and D (assembled and exploded), the containing tube carries the tension reaction.

It has been determined that the design of Fig. 4A exhibits spurious plate-type resonance, but this unsatisfactory condition may be eliminated when one plate is bonded to a metal coupling bar. The design of Fig. 4B has been difficult to evaluate due to a lack of symmetry between the inner tension bolt length and the outer (slugs and ceramic washers)

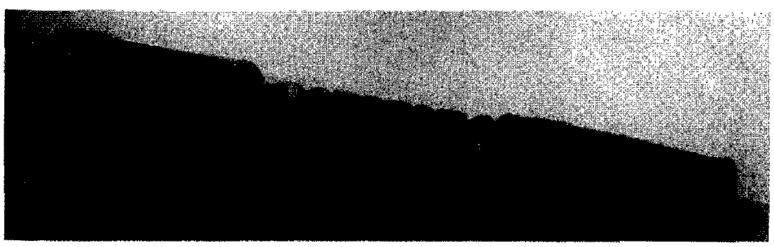


A: PERIPHERAL TENSION BOLTS



B: CENTER TENSION BOLT

C: ASSEMBLED TENSION SHELL



D: TENSION SHELL DISASSEMBLED

Fig. 4: TRANSDUCER DESIGNS INCORPORATING CERAMICS

compression path. Effort will be made to correct these inadequacies as the work proceeds. The design of Fig. 4C and 4D, in which the tension reaction is carried in the enclosing tube, has just been completed and has not been powered for evaluation. These transducers incorporate lead zirconate titanate (obtained from Clevite) into the preloaded type of mechanical assembly which precludes the need of adhesives, offers good probability of satisfactory cooling, and, especially avoids cyclic tension loading of the ceramic elements.

Transducer efficiency will be evaluated by calorimetric investigation with the system of Fig. 3, as discussed in Section IV.

2. Coupling Members

An efficient transducer, while very important, does not insure power delivery to the work pieces. High energy losses can occur in the coupling system between the transducer and the work, especially at high power delivery. Vibratory energy is converted to heat within the coupling system by internal friction. For small deformations (low power) the loss per cycle is low because essentially perfect elastic behavior prevails; at stress levels associated with high power delivery, the problem of internal friction losses is serious.

To our knowledge there is at present no satisfactory theory for internal friction in solids that embraces a broad vibratory frequency spectrum, although such losses can be measured by several experimental methods. For example, at low stress levels (on the assumption of simple harmonic motion) the natural logarithm of the ratio between successive oscillations (log decrement), as determined with a torsional pendulum, may be used to estimate the internal friction losses.

Many investigators (73-75) have worked at frequencies up to about 200 cps, and some work (76) has been conducted at high frequencies. Except for the work by Neppiras (72), little information has been located on the losses in various metallic materials at frequencies in the range of interest, 5-50 kilocycles per second.

Letters were dispatched to both foreign and American individuals and organizations, who, we believe, can supply information on the internal friction losses and acoustic transmissivity of materials in the frequency range of interest.

Parts for a test system designed on the basis of work by Neppiras (72) have been fabricated and await final assembly. This array will be utilized to determine relative, and possibly absolute, acoustic transmissivity of candidate coupler materials. Test specimens of the immediate candidate alloys (tool steel, Monel, and aluminum bronze) have been designed and fabricated.

3. Spot-Type Welder Tips

The problem of attaching welding tips to the sonotrode and/or anvil cannot be ignored; mechanical attachment, while feasible at modest powers, has not been as reliable for higher levels of power; brazing attachment of tips is known to be practical at high power levels. Thus, at least for the present, due to independent considerations, tip materials should be brazable if this is possible.

Information, regarding the various designs of spot-type-welder tips is summarized in Table 17. Mechanically attached tips are highly desirable if not absolutely mandatory. Examples of mechanically attached tips are Types 3 and 6 of Table 17. Type 6 is the more desirable, for a variety of reasons, but, especially, because it can be fabricated easily from small pieces of material (often necessary when a new or special alloy is involved). Type 3, however, is difficult to manufacture and, consequently, is more expensive because a modest quantity of tip material in a variety of shapes is frequently difficult and costly to obtain.

4. Roller-Seam-Welding Disk Tips

While spot-type welding tips constitute such a small part of the welding system that their acoustic properties can be neglected, disk tips for roller-seam welders are a critical factor in resonant systems since they must transmit vibratory energy from the center to a point on the periphery. Disks for roller-seam welding machines are sophisticated, and their design has been the subject of various theoretical treatments and experimental measurements from time to time. Since such disks continually place fresh cool area in contact with the workpiece, they may not involve as rigorous metallurgical and physical demands as spot-type-welder tips. These designs have definite boundary acoustic conditions, however, and because of stress buildup in the center of the disk cannot be indefinitely extrapolated to higher powers. Hysteresis can cause energy to be absorbed within the disk; unstable operation and an unusual type of metallurgical failure may result.

Information concerning various roller-seam-welding tips is summarized in Table 18. The Type 1 tip is an operable nonresonant mass, but any reasonably high welding rate involves an unsatisfactorily high angular velocity of the transducer-coupling system. Types 2, 3, and 4 are characteristic resonant disks, showing several disk-to-coupler attachment methods. Type 5 is a resonant toroid that has received considerable attention.

Table 17

CHARACTERISTICS OF TERMINAL TIP-REED ARRAYS FOR SINGLE-SPOT WELDERS
(Orientation for special applications possible with contoured tips for all types.)

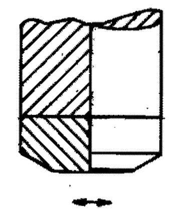
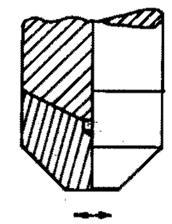
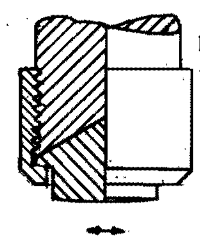
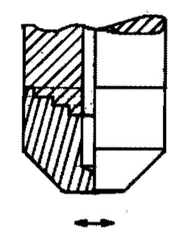
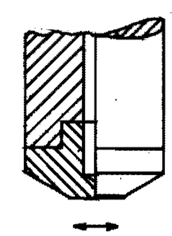
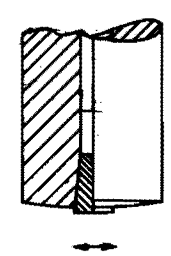
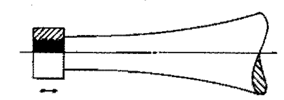
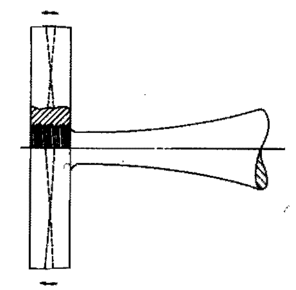
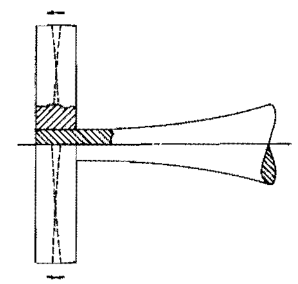
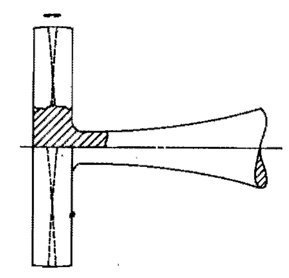
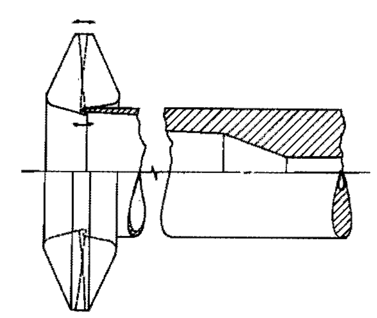
Type	Geometry	Description	Attachment	Ease of Fabrication	Replacement	Mating Junction	Welding Performance	Miscellaneous
1		Spherical or sculptured work surface	Brazed	Relatively easy	Time-consuming		Satisfactory at low power levels	Joint is soft in shear, especially when warm, and its quality is difficult to insure
2		Contoured for greater mating surface	Brazed	Somewhat difficult	Time-consuming	Must be precise. Brazing requires skill.	Satisfactory	Brazed joint is not highly loaded in shear
3		Mechanically attached tip	Threaded	Expensive	Easy	Must be precise	Satisfactory	
4		Multistep tip	Brazed	Difficult	Time-consuming	Must be precise	Satisfactory	Successful in reducing shear load on joint for high-power application
5		Single-step	Brazed	Relatively easy	Time-consuming	Tip easily located for brazing	Satisfactory	Reduced shear load on joint
6		Insert tip	Press-fitted	Difficult		Must be precise	Satisfactory	Insert may be of difficult-to-machine metal. Press-fit or high power may deform thin end of reed

Table 18

CHARACTERISTICS OF TERMINAL TIP-COUPLER ARRAYS FOR CONTINUOUS-SEAM ROLLER WELDERS
(Types 2 to 9 have reduced rotational speed and improved work clearance in comparison to Type 1)

Type	Geometry	Tip	Coupler	Joint	Velocity Transformation Ratio	Ease of Fabrication	Design for Impedance Matching	Miscellaneous	Welding Performance
1		Nonresonant mass	Exponential	Threaded	1.0	Relatively easy	Can be adjusted	Easy to replace	Good, but not consistent over length of seam
2		Resonant flat disk	Exponential	Threaded	0.7	Relatively easy	More difficult than for Type 1	High stresses at junction cause failure Easy to replace	Consistent over length of seam. Satisfactory weld quality
3		Resonant flat disk	Exponential	Brazed	0.7	Relatively easy	More difficult than for Type 1	High stresses at brazed joint Brazed joint has longer life than threaded joint	Consistent over length of seam. Satisfactory weld quality
4		Resonant flat disk	Exponential	Single-piece	0.7	Difficult and/or expensive	More difficult than for Type 1	High stresses at neck. Slightly longer than Types 2 and 3	Consistent over length of seam. Satisfactory weld quality
5		Resonant toroid	Inverted exponential	Brazed	1.15	Difficult and/or expensive	More difficult than for Type 1	Highly stressed center disk area eliminated Serious microkinematic problems at junction cause failure	Consistent over length of seam Power delivery superior to that of disks up to 2000 w Satisfactory weld quality

APPENDIX

THE LIMITATION ON AMPLITUDE SET BY MAXIMUM
STRAIN ENERGY IN VIBRATING SYSTEMS

PUBLISHED IN NYO REPORT 9588, "APPLICATIONS OF ULTRASONIC ENERGY" (#5)

In many applications of ultrasonics it is desirable to achieve as great an amplitude of oscillation at the work area as is permitted by the elastic properties of the materials constituting the vibrating system. It is assumed in this analysis that a given isotropic material is characterized by a maximum permissible oscillating elastic strain energy density, which can not be exceeded without fatigue failure, regardless of whether the energy density is associated with shear distortion, simple compression, or a combination of the two. The treatment can be modified later, if it turns out that the fatigue limit depends on the nature of the elastic distortion.

Longitudinal Vibration of a Uniform Bar

Consider first the longitudinal vibration of a slender half-wave rod of uniform section. The strain at any position X, with origin at the center of the rod, is

$$\frac{\partial \xi}{\partial X} = \left(\frac{\partial \xi}{\partial X}\right)_m \cos K X, \qquad (1)$$

where X has the range $-\lambda/4 \leq X \leq \lambda/4$,

$$K = \frac{2\pi}{\lambda} = \frac{\omega}{c}, \qquad (2)$$

and $c = \sqrt{E/\rho}$ as usual.

The maximum amplitude at the end of the rod is

$$A_m = \left(\frac{\partial \xi}{\partial X}\right)_m \int_0^{\frac{\lambda}{4}} \cos K x \, d X = \frac{1}{K} \left(\frac{\partial \xi}{\partial X}\right)_m . \tag{3}$$

The maximum elastic energy density at the center is

$$\mathcal{E}_m = \frac{1}{2} E \left(\frac{\partial \xi}{\partial X}\right)_m^2$$

where E is Young's Modulus; (4)

hence,

$$\mathcal{E}_m = \frac{1}{2} E K^2 A_m^{\ 2} = \frac{1}{2} \rho \, \omega^2 A_m^{\ 2} . \tag{5}$$

Since the maximum velocity at the end of the rod is $\omega A_m = \dot{\xi}_m$, Eq. 5 can be written

$$\mathcal{E}_m = \frac{1}{2} \rho \, \dot{\xi}_m^{\,2} , \tag{6}$$

which is the kinetic energy per unit volume of the material at the end of the rod. Whereas the kinetic energy density and velocity is independent of frequency for a given upper limit to $\mathcal{E}_m$, the permissible amplitude varies inversely with frequency.

Lateral Vibration of a Uniform Bar

Next the free-free lateral vibration of a bar of circular section. The following results from Rayleigh, p. 281 et seq., (77) can be used. For the frequency,

$$\omega = \frac{1}{2} (4.73)^2 \frac{a}{\ell^2} \sqrt{\frac{E}{\rho}} . \tag{7}$$

For the amplitude at the end, in terms of the amplitude at the center,

$$A_{end} = 1.645\, A_{center} . \tag{8}$$

From the table on p. 282 of Rayleigh (77), by taking second differences,

$$\left(\frac{\partial^2 \eta}{\partial x^2}\right) = \frac{29.1}{\ell^2} A_{center} = \frac{17.7}{\ell^2} A_{end}. \tag{9}$$

The maximum fiber strain at the center is

$$\left(\frac{\partial \xi}{\partial x}\right)_m = a \left(\frac{\partial^2 \eta}{\partial x^2}\right)_{center} = 17.7 \frac{a}{\ell^2} A_{end} \tag{10}$$

On combining (7) and (10)

$$\left(\frac{\partial \xi}{\partial x}\right)_m = 1.54 \sqrt{\frac{\rho}{E}}\ \omega A_{end} \tag{11}$$

Hence, from Eq. (4)

$$\mathcal{E}_m = 2.37 \left[\frac{1}{2} \rho\, \omega^2 A_{end}^2\right]. \tag{12}$$

This result shows that for a given amplitude at the end, the (surface) strain-energy density at the center is nearly two and one-half times as great as for the longitudinal case. It depends on density and frequency as before, a result that is obvious from dimensional considerations.

If the bar is of rectangular section, of thickness 2a, Eq. (7) becomes

$$\omega = \frac{1}{\sqrt{3}} (4.73)^2 \frac{a}{\ell^2} \sqrt{\frac{E}{\rho}} , \tag{13}$$

since the radius of gyration of the section is now $a/\sqrt{3}$ instead of $a/2$..

Hence, the value of a/ℓ^2 in Eq. (10) is decreased by the factor $\sqrt{3}/2$ (for a given frequency) and the energy density of Eq. (12) by $(\sqrt{3}/2)^2 = 0.75$. Accordingly, a rod of rectangular section is superior to one of circular section, when as large an amplitude of vibration as possible is desired.

Axial Vibration of a Thin Uniform Disk

It can be shown (78) for one nodal circle with $\sigma = 1/3$ that

$$\omega = 2.615 \frac{t}{a^2} \sqrt{\frac{E}{\rho(1-\sigma^2)}} \tag{14}$$

where a is the radius and t, the thickness of the disk. The shape of the disk is given by the function

$$W = J_o(kr) + \lambda I_o(kr); \tag{15}$$

with $k^4 = \omega^2/\alpha^4$,

$$\alpha^4 = \frac{E\,t^2}{12\,\rho(1-\sigma^2)}$$

$$\lambda = -\frac{J_1(ka)}{I_1(ka)}$$

where the J and I function are ordinary and modified Bessel functions, respectively. For $\sigma = 1/3$, $ka = 3.01$ and $\lambda = -0.0841$. The amplitude at the edge is 0.74 that at the center.

A calculation based on Eq. (15) shows that the curvature at the center, for a displacement amplitude A_{center}, is

$$\frac{\partial^2 W}{\partial r^2} = \frac{1}{2} k^2 \frac{(1-\lambda)}{(1+\lambda)} A_{center}. \tag{16}$$

The strain at the surface is, therefore,

$$\left(\frac{\partial \xi}{\partial X}\right)_m = \frac{t}{2}\,\frac{\partial^2 W}{\partial r^2} = \frac{1}{4}\,\frac{t}{a^2}\,(3.01)^2\,\frac{1.084}{.916}\,\frac{A_{edge}}{0.74} = 3.62\,\frac{t}{a^2}\,A_{edge}, \tag{17}$$

on introducing the numerical values already quoted for ka, λ and A_{edge}/A_{center}. The strain energy density for a plate stretched uniformly in all directions an amount $\partial\xi/\partial X$ is

$$\mathcal{E} = \frac{E}{1-\sigma}\left(\frac{\partial \xi}{\partial X}\right)^2. \tag{18}$$

On introducing the value from Eq. (17), for $\partial\xi/\partial X$, the frequency from Eq. (14), and $\sigma = 1/3$,

$$\mathcal{E}_m = \frac{E}{1-\frac{1}{3}}\,(3.62)^2\,\frac{\rho(1-\frac{1}{3}^2)}{E}\,\frac{\omega^2}{(2.615)^2}\,A^2_{edge} = 5.10\left[\frac{1}{2}\,\rho\omega^2\,A^2_{edge}\right]. \tag{19}$$

Hence, for a given amplitude at the edge, the maximum strain energy density is slightly more than five times that of the longitudinal case for the same amplitude and frequency.

EXTENSION OF PUBLISHED WORK

Torsional Vibrations of a Uniform Rod

Consider, finally, the torsional vibrations of a uniform half-wave rod of circular section, with origin at the center. If θ is the angular displacement at any section, the angular strain is

$$\frac{\partial\theta}{\partial X} = \left(\frac{\partial\theta}{\partial X}\right)_m \cos K X, \tag{20}$$

and the angular amplitude at the end is

$$\theta_m = \left(\frac{\partial\theta}{\partial X}\right)_m \int_0^{\frac{\lambda}{4}} \cos K X \, dX = \frac{1}{K}\left(\frac{\partial\theta}{\partial X}\right)_m. \tag{21}$$

The linear amplitude at the outer radius a is

$$A_m = a\,\theta_m = \frac{a}{K}\left(\frac{\partial \theta}{\partial X}\right)_m = \frac{1}{K}\left(\frac{\partial \mathcal{J}}{\partial X}\right)_m, \tag{22}$$

where $(\partial \mathcal{J}/\partial X)_m$ is the maximum shear strain at the surface of the rod. Since the strain energy density is

$$\mathcal{E} = \frac{1}{2}\mu\left(\frac{\partial \mathcal{J}}{\partial X}\right)^2, \tag{23}$$

from Eq. (22) and (23), by substituting $K = \omega/c_t$ and $c_t = \sqrt{\mu/\rho}$,

$$\mathcal{E}_m = \frac{1}{2}\rho\,\omega^2 A_m^{\ 2}. \tag{24}$$

The torsional case, therefore, is identical with the longitudinal case discussed in the first section, the longitudinal vibration of a uniform bar, of the published material. All of the results obtained show that $\mathcal{E}_m/\rho$ is a figure of merit for an elastic material, which can be used to estimate the largest possible vibratory amplitude at a given frequency, regardless of the geometry of the vibrator.

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